Thermalization of nuclear matter in heavy-ion collisions at Fermi energies

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Heavy-ion collisions (HICs) are widely used to produce and analyze the properties of nuclear matter under various conditions of temperature and baryon density. The nuclear fireballs created in these reactions are governed by strong nuclear interactions and have been observed to reach local thermal equilibrium at ultra-relativistic bombarding energies [1]. Thermalization of the nuclear medium is not as clear, however, at lower energies, $E_{lab} < 1$ A•GeV [2]. In this work [3], we investigate nuclear matter as produced in HICs at low beam energies, i.e., $E_{lab} = 35$ MeV/A.

Toward this end, we employ transport simulations of central ^{40}Ca+^{40}Ca collisions using the Constrained Molecular Dynamics (CoMD) approach [4]. Specifically, we extract the isospin, position, and momentum of all nucleons during the collisions and perform a coarse-graining procedure [5,6] where the center of the collision is partitioned into eight cubic cells adjacent to the origin, each of volume 8 fm^3. In each cell the 3-momenta of the nucleons are binned to provide localized momentum distributions that we fit with a thermal ansatz, allowing, however, for off-equilibrium features. It turns out that the distributions in the transverse (x- and y-) directions are amenable to thermal fits (cf. Fig. 1 left), with Fermi distributions performing much better than Boltzmann ones, a consequence of the Pauli blocking implemented in CoMD. However, along the z-axis (beam axis) off-equilibrium features are apparent, most notably the centroid motion of the two incoming nuclei and a slight narrowing of the distributions relative to the temperatures extracted from the transverse direction, which we account for by a superposition of two momentum-shifted distributions (cf. Fig. 1 right).

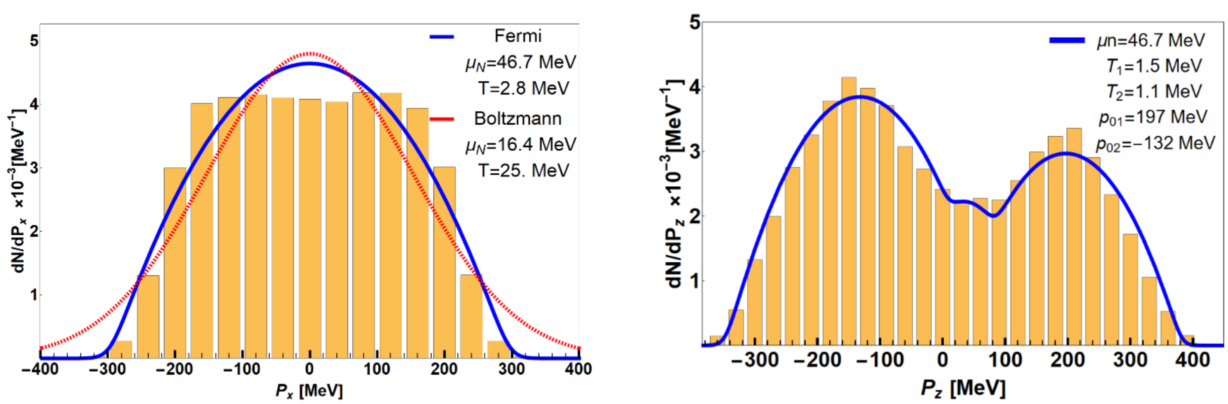

Fig. 1. Left panel: Our fits using Fermi (blue lines) or Boltzmann distributions (red dotted line) for the transverse-momentum distributions in the x-direction (left panel) compared to the CoMD transport output (orange histogram) at 65 fm/c (corresponding to maximal density). Right panel: Comparison of the Fermi fit function for the longitudinal momentum distributions (blues line) with centroid motion (characterized by parameters $p_{01,02}$) to the transport output (orange histogram) at 65 fm/c. The nuclei (when treated as classical spheres) begin to touch at t≈44 fm/c, and full overlap of the two nuclei happens at t≈77 fm/c.

From the parameterized Fermi distributions, the time evolution of the fitted parameters can be extracted, cf. Fig. 2. Initially, most of the kinetic energy of the nucleons is contained in the form of the incoming motion of the nuclei. Shortly after the initial impact, this “directed” energy starts to dissipate

Fig.

into "random" kinetic energy, and the nuclear medium starts to rapidly heat up. This process is completed at about 150 fm/c after initial impact at which point the temperature essentially plateaus. Our analysis thus gives a novel insight about the timescale of thermalization in Fermi energy nuclear collisions, made possible by the implementation of off-equilibrium effects in the longitudinal direction, as well as employing substantially smaller coarse-graining volumes than in previous extractions of thermodynamic parameters at these energies [7,8].

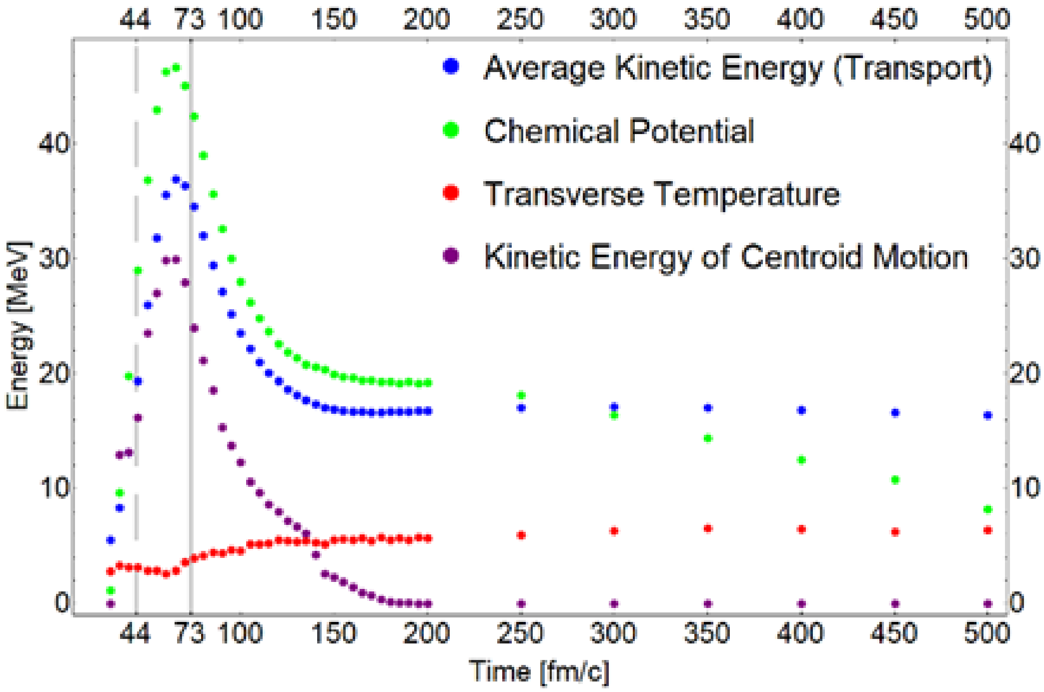

Fig. 2. Time evolution of thermodynamic properties of nuclear matter extracted from the collision center of CoMD transport simulations of 35 A·MeV ^{40}Ca +^{40}Ca collisions: average total kinetic energy (blue dots), nucleon chemical potential (green dots) and temperature (red dots) from fits of the transverse-momentum spectra, and the kinetic energy of the motion of the two centroids in the longitudinal direction (purple dots). The vertical dashed and solid lines indicate when the nuclei first touch and fully overlap, respectively.

In summary, by employing a coarse-graining procedure to CoMD transport simulations of nuclear collisions at Fermi energies, we have been able to fit thermal distribution functions to nucleon transverse-momentum spectra. Upon implementing off-equilibrium effects to account for motion of the incoming nuclear centroids, we have also achieved a fair description of the p_z dependence of the distribution functions. The time evolution of the extracted parameters for temperature, chemical potential and nuclear-centroid momenta enabled to systematically track the conversion of the incoming longitudinal energy into thermal motion. We also plan to utilize the distributions for an analysis of photon spectra using a field-theoretic calculation of local emission rates.

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